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Optimizing Pumping Strategies for Contaminant Studies and Remedial Actions

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16. ABSTRACT

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Optimizing Pumping Strategies for Contaminant Studies and Remedial Actions

by Joseph F. Keely

Abstract

One of the more common techniques for controlling the migration of contaminant plumes is the use of pumping wells to produce desired changes in local flow rates and hydraulic gradients. When seeking to optimize an array of pumping well locations and discharge rates, it is important to consider the effects that non-ideal aquifer conditions, well construction and demographic constraints produce. Heterogeneous and anisotropic aquifer conditions seriously complicate siting and discharge rate requirements for pumping wells because of the distorted cones of depression that result from withdrawing water in such settings. Proper screen selection, gravel pack emplacement and well development are crucial factors affecting the operational characteristics and economics of pumping wells; these factors are generally recognized, though often undervalued. The impacts that well depth and diameter, and screen length and position have on the effectiveness of pumping efforts are also often undervalued, with detrimental consequences. Perhaps the most difficult problems to overcome in designing pumping schemes, however, are posed by demographic constraints. Denial of property access, vandalism and the unpredictability of nearby water supply and irrigation pumpage tend to wreak havoc with the best of pumping strategies.

Introduction

Safe storage and disposal of hazardous wastes have become major social issues because of the discovery that many sites lack proper precautions for the prevention of soil and water contamination. Ground water contamination has received the major share of society's attention to these issues, primarily because the route of human exposure by this pathway is direct. In practical terms, this means that the level of cleanup of the damage done by contamination incidents is often dictated by social concerns (e.g. health risk). Plume stabilization by interception and control with perimeter wells, injection and recovery loops, and other pumping schemes may be chosen as the "remedial action" appropriate for a particular plume. The affected plume may be held in place and treated, it may be held and allowed to move on after alternate public supplies have been located for downgradient water systems, it may be held in place to allow biodegradation of particular constituents, or it may be held until better treatment procedures can be devised.

Factors Affecting Pumping Strategies

Hydrodynamic control and recovery strategies vary considerably in their efficiencies. Besides the obvious need to choose the well locations and flow rates carefully, a number of other considerations demand attention (Figure 1). Non-ideal aquifer conditions are a reality for virtually all real-life situations; heterogeneity is the rule rather than the exception. Three-dimensional anisotropy, as expresed by the vertical vs. horizontal hydraulic conductivity ratio, is a near certainty for most strata. Less visibly pronounced, yet almost as prevalent, is an expressed anisotropy in the horizontal plane of many strata. These commonplace non-ideal aquifer conditions complicate our perception of where a given plume can go (Fetter 1981) under both natural flow conditions and remedial action pumping schemes. The preferential flow paths that are created by buried lake beds, glacial outwash gravels, streambeds, coastal deposits and the like cannot be delineated without expensive and time-consuming field tests. Likewise, it is nearly impossible to accurately predict the magnitudes of distortion in the cones of depression created by wells pumping from heterogeneous, anisotropic aquifers.

Variations in the properties of the fluid in an aquifer, particularly the solution density, also can significantly affect the behavior of contaminant plumes (Jorgenson et al. 1982). Immiscible plumes with lower density than that of the native ground water will float at the surface of the saturated zone, traveling along the same general gradient, but traveling

at a different rate than the underlying ground water. Immiscible plumes with greater density than that of the native ground water will sink through the ground water, losing small but significant amounts of low solubility constituents as they move. Miscible plumes of any density, by definition, mix intimately with native ground water. The duration of time required to achieve a specific dilution by this mixing changes markedly, however, and is generally inversely related to the density. For most situations, the greater the density, the shorter the mixing period. The exception to this general rule would be the case of a large volume of highly dense, miscible fluid penetrating a shallow aquifer quickly enough to reach bedrock in a relatively undisturbed form.

Considerations

Non-Ideal Aquifer Conditions:
- Heterogeneity
- Anisotropism
- Variable density

Well Construction Effects:
- Partial penetration
- Partial screening
- Incomplete development

Anthropogenic Influences:
- Property access
- Vandalism
- Unknown pumpage/injection

Other Factors:
- Physiochemical attenuation
- Biological transformations
- Operational failures

Figure 1. General considerations for optimizing pumping strategies

These complexities work against us if we are ignorant of them. Working up an appropriate recovery system for a contaminant plume can be compared to designing an oil production system. What you get out depends directly on what you put in—up to a point. Where that break-even point comes is hard to say, given unknowns like the source strength and timing, and immeasurables like the dollar value of additional cancer victims. What is abundantly clear, however, is that there is a substantial minimum for serious play. One does not blithely draw up plans to pump and treat a plume until considerable manpower and funds are expended to obtain information on the natural flow direction, gradient and velocity. The question is usually one of how much to spend to reach some desired level of detail; the level of detail is set by social concerns.

This seems to be logical application of technology for social need, but the logic may be shortsighted. If social concerns (based on preliminary evaluation of a contaminant incident) are minimal, there is no guarantee that such social concerns are appropriate. Additional studies, which could delineate preferential flow paths and quantify factors affecting contaminant behavior, might well generate findings that would justify considerably greater or lesser social concern. Quite often data from preliminary investigations are limited to samples from shallow on-site wells, which may fail to signify the potential impact of dense plumes or seasonally-occurring leachate plumes that have moved off-site. Additionally, the preliminary investigation wells are not normally installed to a sufficient depth for appreciation of the local stratigraphic and lithologic characteristics of the aquifer.

In addition to a better understanding of where contaminants might go with the natural flow, a second powerful argument to avoid "penny-wise and pound-foolish" investigations concerns the need to provide the best information possible for targeting well locations and pumping strengths in remedial actions. The occurrence of specific heterogeneities can be used to advantage by locating wells near low permeability clay units to generate greater drawdown for a given pumping rate. Likewise, knowledge of the direction of the principal horizontal axis in anisotropic strata can help to maximize the arrangement of the "troughs of depression" for wells to be located in such settings; knowledge of the magnitude of vertical anisotropy can help determine the amount of water pumped from strata containing contaminants vs. the amount of "clean" water from the other strata open to the well.

This latter factor, vertical anisotropy, leads to examination of some of the more controllable items to be considered in optimizing pumping strategies—well construction effects. For example, the impact that partial penetration of a fully screened pumping well can have on the estimate of potential for contamination of a water supply or on the effectiveness of a remedial action scheme is tremendous (Saines 1981). The effect is to cause exaggerated drawdowns near the well. The magnitude of the effect is inversely dependent on the degree of penetration of the well into the aquifer, being greatest for slight penetration. Naturally, partial screening of a fully penetrating well results in the same effect—greater drawdown for a given pumping rate as compared with a fully screened, fully penetrating well.

Again, knowledge of these factors can be used to enhance a pumping scheme that is, for example, designed to maintain hydrodynamic control of a plume at the lowest possible level of pumpage. Lack of appreciation of these well construction effects can result in poor estimates of potential contaminant impacts on supply wells and in poorly designed remedial action schemes. Another effect worthy of mention is that generated by well development practices. If a well is properly developed, the drawdown measurable inside the well will agree with the level projected by close observation wells. More often, however, a well is not perfectly efficient because the well development procedures were not adequate to remove drilling fluid fines and locally disturbed aquifer material resulting from the drilling process. These materials lower the permeability of the gravel pack and formation immediately adjacent to the well. The greater the degree of well inefficiency caused by lack of proper development, the greater the amount of non-productive drawdown inside the well; this means that the well may never be able to pump at design capacity without risk of running dry, and it means increased operating expense due to the additional pump lift required. What it may also portend, for seriously inefficient wells, is that certain strata penetrated by the well may be effectively sealed by drilling mud or by natural clays that were smeared over the borehole face by the actions of the drilling operation. Such "sealed off" strata may carry the bulk of the contaminants, resulting in poor recovery of the plume.

Some of the most significant, though less controllable, factors that should be considered when optimiz-

ing pumping strategies concern direct anthropogenic influences: denial of property access, vandalism and unknown pumpage all tend to wreak havoc with the best laid plans. Bedient et al. (1984) describe efforts to delineate a plume of contaminants migrating under a residential area from an abandoned wood creosoting plant in Conroe, Texas:

> "Several wells exist in the general flow direction, but not directly downgradient from the waste pit locations. Access was not granted for installing monitoring wells . . . Approximately 50 percent of the chloride plume has been defined since the monitoring well network is incomplete at this time . . . Completion of the monitoring well network is needed to capture the center of the contaminant plume. This will require more wells downgradient on land that has not previously been accessible for investigation."

The granting of property access during investigations of ground water contamination incidents in populated areas is no trivial matter. One typically finds it necessary to contact not only homeowners and landlords for private property access, but also to negotiate with company engineers, vice presidents and attorneys for commercial property access. It is quite normal for such negotiations to be involved and protracted as city councils, educational boards, corporate headquarters and other bureaucratic entities are asked to concur in signing access agreements containing provisions deemed necessary to ensure against incurred liability and potential damage.

The role played by unknown pumping and/or injection wells operating near a remedial action pumping system is subtle but far-reaching. Such unknown stresses can significantly distort the flow field and render remedial actions ineffective. Projections on plume movement made during an investigation of a ground water contamination incident would also be in error if unknown wells are causing distortion in the flow field; both the direction and the speed of the plume could be dramatically altered. The reason for the subtlety of the effects of many such wells is that their cyclic, seasonal or on-demand pumping schedules allow them to be detected only by continuous recording of water level changes at numerous points around the zone of interest. Since aquifer responses at a given observation point are somewhat non-unique, merely detecting extraneous sources of drawdown does not automatically result in identification of the sources.

There are a few other important factors to consider that also affect pumping strategies. The physiochemical properties of the contaminant itself can result in a need to pump several pore volumes from each unit volume of aquifer to be decontaminated. Sorption, ion exchange and speciation changes can result in retarded movement of contaminants relative to the average velocity of the water with which they are initially associated. Biotransformation of contaminants may result in reaction products (daughter products) that are of greater or lesser toxicity, mobility and persistence—in other words, uncertain contaminant behavior. Unlike the aquifer properties of storage coefficient, saturated thickness and hydraulic conductivity, which can be readily determined, the current state-of-the-science with regard to determining the potentials for physiochemical attenuation and biotransformation is not up to the level of routinely providing reliable answers on a site-specific basis.

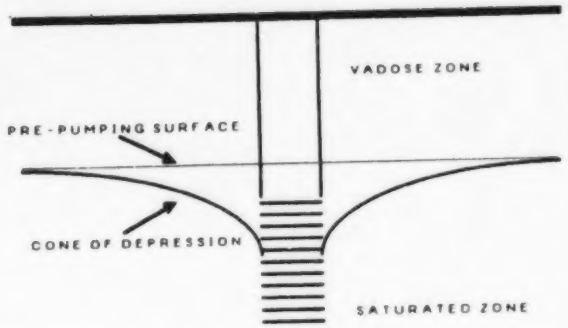
Finally, an obvious but often overlooked consideration involved in optimizing pumping strategies is the need to develop adequate contingencies for operational failures. This means some intentional overdesign for reserve capacity, total redundancy of key wells and electronic controls, backup power systems and so on. It also means bonding or insurance against unforeseen catastrophies so that as little downtime is expended as possible. It may also mean that an escrow account or trust fund must be established to provide the necessary capital for replacement of burned-out or inadequate pumps, deepening or abandonment of existing wells, or drilling of additional wells.

Capture Zones vs. Zones of Pressure Influences

Keely and Tsang (1983) introduced the term "capture zone" to describe that portion of the aquifer affected by pumping which actually yields water to the well. They have shown that the capture zone is generally much smaller than the zone of pressure influence because a balance is achieved, under steady-state conditions, between the pull of water back toward the well from its downgradient side and the tendency of the natural flow system to move on further downgradient. Figure 2 is a series of four idealized illustrations that present conceptualizations of how the size of the capture zone changes, relative to the zone of pressure influence/cone of depression, as the local gradient is increased. In Figure 2A the well is pumping from a stagnant aquifer, indicated by the flat pre-pumping surface, overlaid on the theoretical cone of depression that would occur during pumpage. For stagnant aquifer conditions, the capture zone is everywhere identical to the zone of pressure influence and flow is radial into the well. As the successive diagrams indicate, however, non-stagnant aquifer conditions lead to smaller capture zones (Figures 2B to 2D).

The slopes of the pre-pumping surfaces are overlaid on the theoretical drawdown cones in each frame of Figure 2 to emphasize the interaction of the natural flow system with the pumping stress to yield a capture zone smaller than the zone of pressure influence. There is no intention to show the net surface resulting from pumpage by subtracting theoretical drawdown values from pre-pumping water elevations. These sketches do have the cosmetic drawback of showing crossing water level lines/curves, but the point is to illustrate the individual components of the net surface (cross-sectional view) and how they interact to yield a capture zone (three-dimensional view).

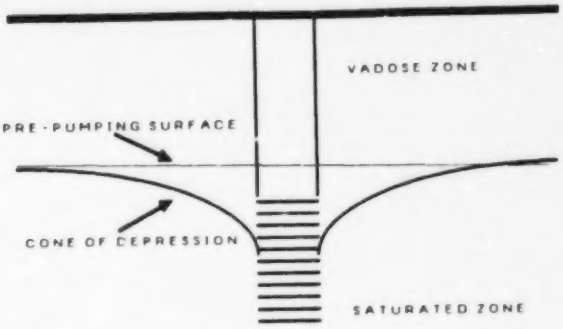
The flow lines generated by pumping a well from an idealized aquifer (homogeneous, isotropic, constant density, etc.) under different natural flow conditions are shown in Figure 3. In Figure 3 a well pumping 1,000m^3/day from a 10m thick aquifer having a porosity of 0.10 and a hydraulic conductivity of 100m/day has uniform radial flow under stagnant aquifer conditions (e.g. natural flow velocity equal to zero). When a mild hydraulic gradient (0.0001) is imposed on the same system (Figure 3B), the resulting natural flow velocity (0.1m/day) is insufficient to significantly affect the flow lines, and uniform radial flow is nearly maintained. With a more moderate hydraulic gradient (0.001), the resulting natural flow velocity (1.0m/day) is sufficient to sweep away many of the flow lines and the capture zone is clearly evident (Figure 3C). Where a steep gradient (0.01) is present, the capture zone diminishes to a small fraction of the zone of pressure



CROSS-SECTIONAL CONCEPTUALIZATION

THREE DIMENSIONAL CONCEPTUALIZATION

Figure 2A. Stagnant aquifer conditions



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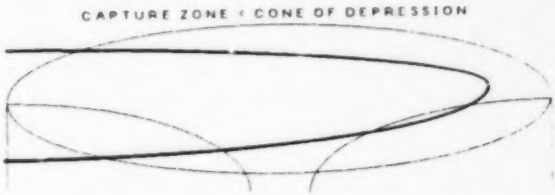
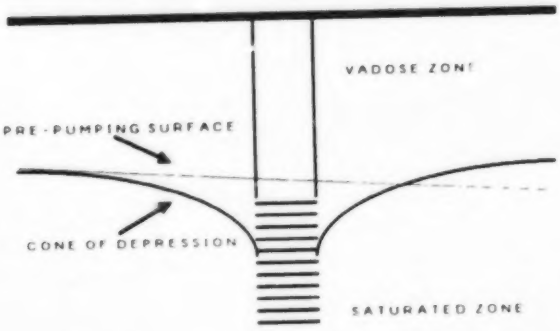
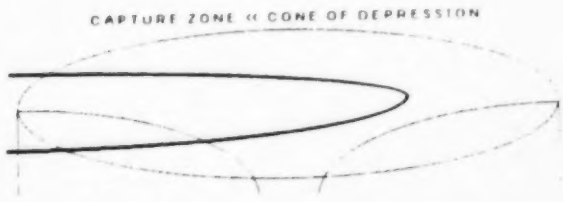


THREE DIMENSIONAL CONCEPTUALIZATION

Figure 2B. Mild natural gradient

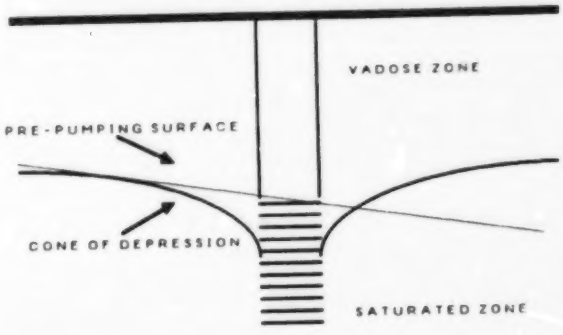


CROSS-SECTIONAL CONCEPTUALIZATION



THREE DIMENSIONAL CONCEPTUALIZATION

Figure 2C. Moderate natural gradient



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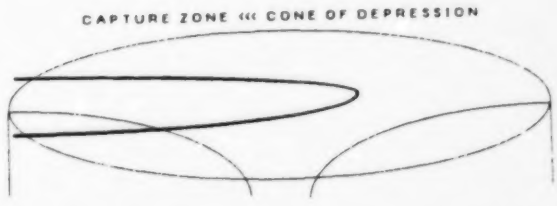

THREE DIMENSIONAL CONCEPTUALIZATION

Figure 2D. Steep natural gradient

Figure 2. Cross-sectional and three-dimensional conceptualizations of capture zone vs. cone of depression

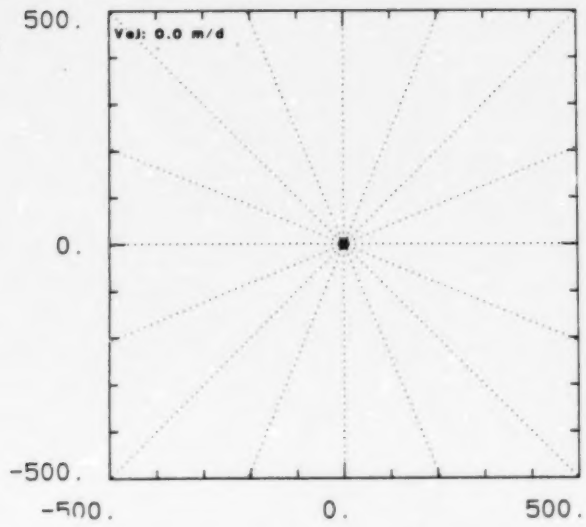

Figure 3A. Stagnant aquifer conditions

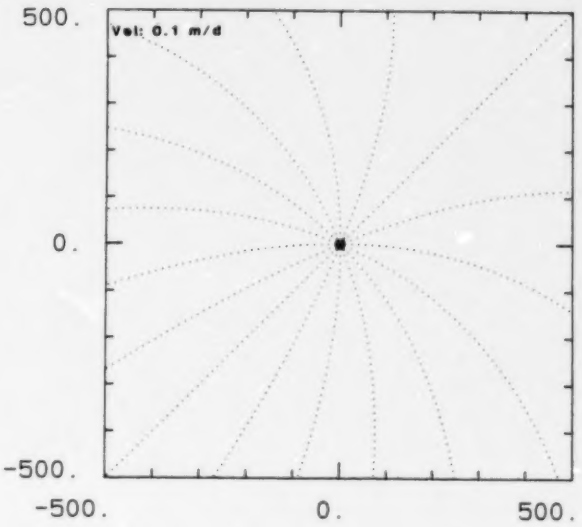

Figure 3B. Mild hydraulic gradient (0.0001)

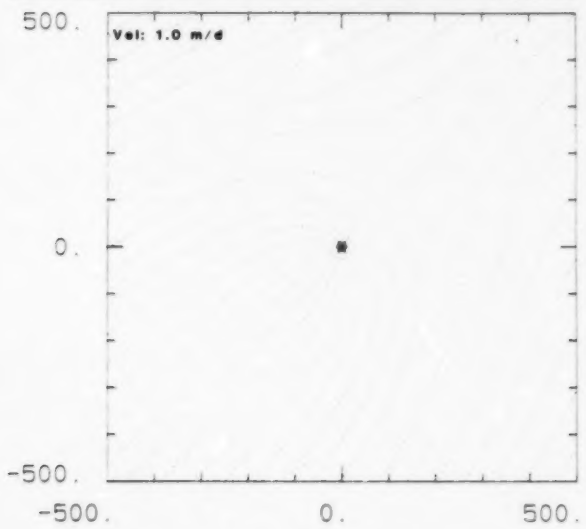

Figure 3C. Moderate hydraulic gradient (0.001)

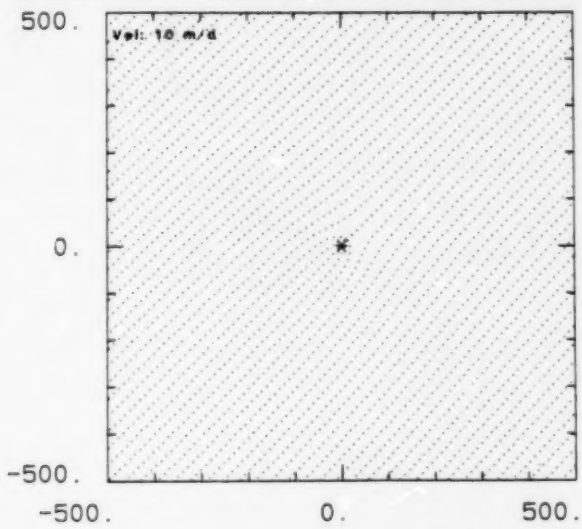

Figure 3D. Steep hydraulic gradient (0.01)

Figure 3. Flow line plots for a single well discharging 1,000m³/day from an aquifer with 10m saturated thickness, 100m/day hydraulic conductivity and 0.10 porosity

NOTE: Scale is in meters and natural flow proceeds from lower left-hand corner to upper right-hand corner of each plot at the velocity indicated.

influence (Figure 3D).

Comparing Pumping Strategies

A typical use of pumping schemes is to effect hydrodynamic control over a plume, either for long-term stabilization or for withdrawal and treatment. Consider extending the example illustrated by Figure 3. First, assume a line of five wells lying perpendicular to the direction of natural flow (Figure 4). Each of the five wells pumps 200m³/day, so that the total pumpage of the five wells is the same as that of the single well in Figure 3. Under stagnant aquifer conditions to low natural flow velocities (Figures 4A and 4B) there does not seem to be any difference in the effectiveness of the pumpage from the five wells as compared with the single well case (Figures 3A and 3B). The situation changes markedly if moderate to high natural flow velocities are present, however, as depicted in Figures 4C and 4D. As the natural flow velocity increases, the capture zone of each of the five wells diminishes to a point where adjacent capture zones no longer overlap and natural flow lines run on through the line of wells. By contrast, the capture zone of the single well pumping 1,000m³/day does not develop holes, but does diminish in size to well below the perceived size of the leaky collective capture zone of the line of five wells.

In actuality, there is no difference between the true collective size of the capture zones generated by the five wells and that generated by the single, high-flow

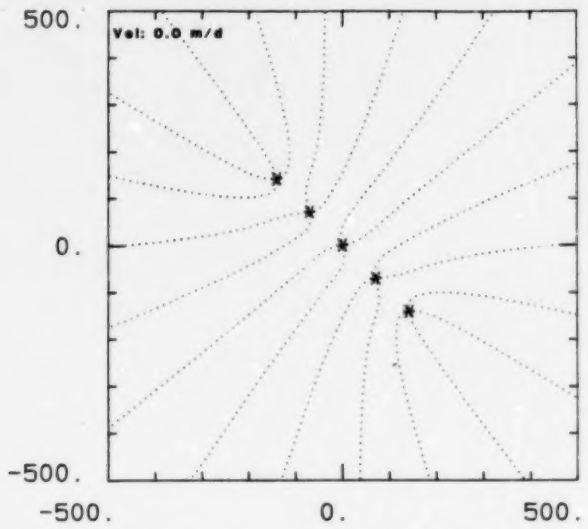

Figure 4A. Stagnant aquifer conditions

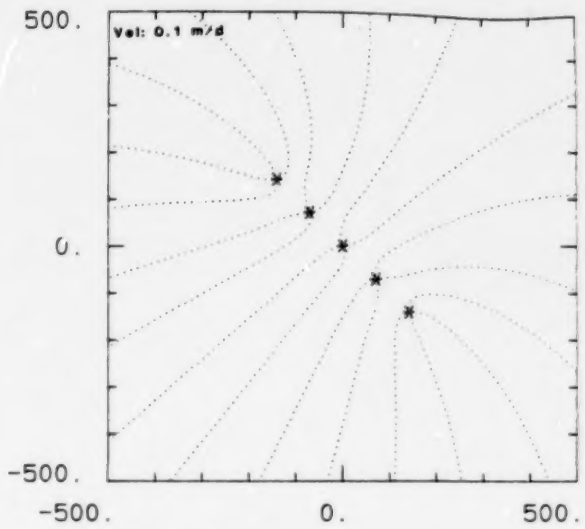

Figure 4B. Mild hydraulic gradient (0.0001)

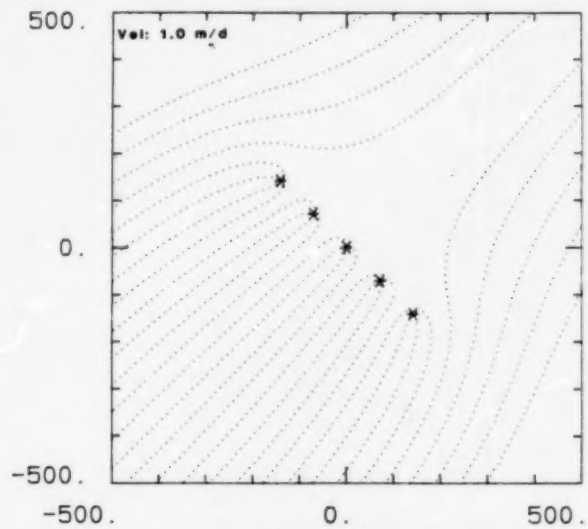

Figure 4C. Moderate hydraulic gradient (0.001)

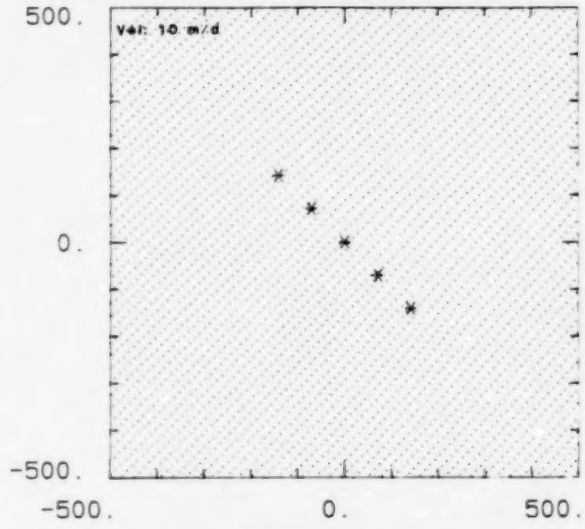

Figure 4D. Steep hydraulic gradient (0.01)

Figure 4. Flow line plots for a line of five wells, each discharging 200m³/day from an aquifer with 10m saturated thickness, 100m/day hydraulic conductivity and 0.10 porosity

NOTE: Scale is in meters and natural flow proceeds from lower left-hand corner to upper right-hand corner of each plot at the velocity indicated.

rate well. By rearranging some of the expressions for capture zone dimensions given by Keely and Tsang (1983), it is possible to define the maximum width of the capture zone upgradient of the well as: $W_{max} = Q \div (h\phi_e V_{nat})$. Using this relationship, it is apparent that the maximum width (W_{max}) of the capture zone of a well is directly and linearly related to its flow rate (Q), and is inversely related to the natural flow velocity (V_{nat}).

For the example discussed here regarding a single well pumping 1,000m³/day, the maximum width of the capture zone is 1,000m when the natural flow velocity is 1.0m/day, and is 100m when the natural flow velocity is 10m/day. Each of the five wells in the second example discussed pumps at a flow rate equal to one-fifth the flow rate of the well in the first example (200m³/day), and each, therefore, has a capture zone the maximum width of which is one-fifth that of the single well (200m). Hence, by comparing Figure 3 with Figure 4, it is seen that the way in which the total pumpage is distributed does directly affect the distribution of the capture zone(s), but does not affect the magnitude or total area of the capture zone(s). Also to be seen in Figures 3 and 4 is that increasing the natural flow velocity estimate can have a dramatic impact on the effectiveness of the pumping strategy. Given the order-of-magnitude uncertainty so often associated with hydraulic conductivity estimates, it is not surprising that many seemingly acceptable remedial action schemes are doomed to fail miserably.

A more complicated example provides further illustration of these points. Assume that we have the same

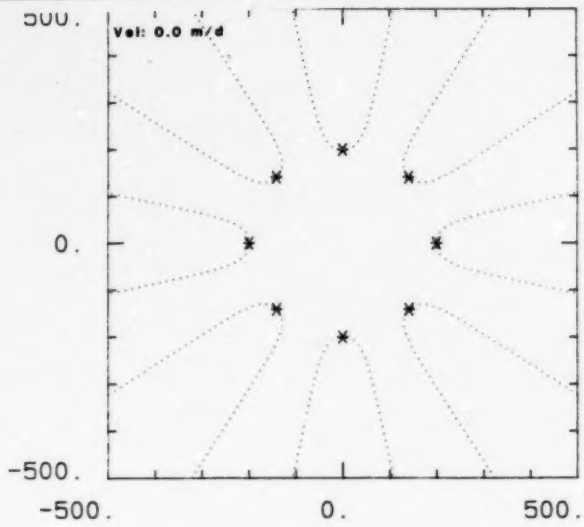

Figure 5A. Stagnant aquifer conditions

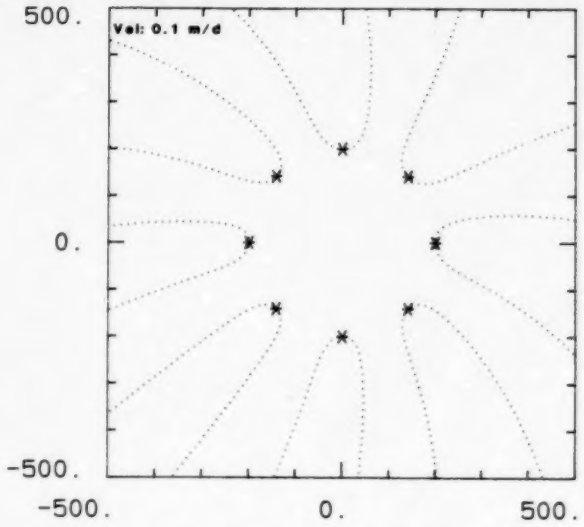

Figure 5B. Mild hydraulic gradient (0.0001)

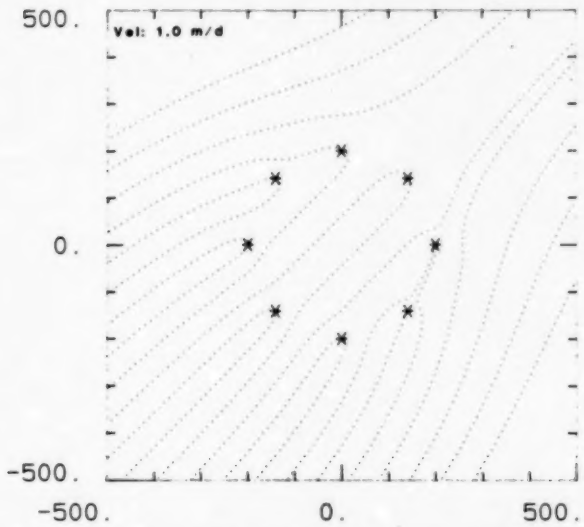

Figure 5C. Moderate hydraulic gradient (0.001)

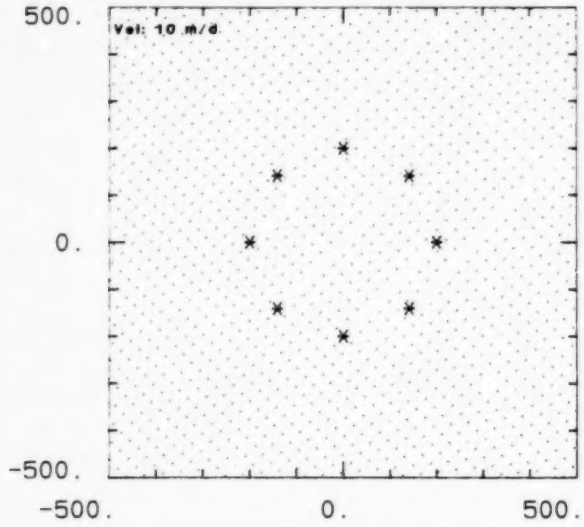

Figure 5D. Steep hydraulic gradient (0.01)

Figure 5. Flow line plots for a circle of eight wells, each discharging 125m³/day from an aquifer with 10m saturated thickness, 100m/day hydraulic conductivity and 0.10 porosity

NOTE: Scale is in meters and natural flow proceeds from lower left-hand corner to upper right-hand corner of each plot at the velocity indicated.

aquifer conditions and total pumpage limitation (1,000m³/day) as the preceding examples. We will distribute the pumpage uniformly by pumping each of eight wells at 125m³/day. The eight wells are evenly spaced around a circle of 200m radius. We are trying to hold a plume within the circle. With stagnant aquifer conditions to low natural flow velocities, the plume appears to be stable; no flow lines pass through the circle (Figures 5A and 5B). At moderate to high natural flow velocities, however, the situation is quite different; flow lines readily pass through the circle, indicating that the plume stabilization attempt has failed (Figures 5C and 5D).

A pump and treat scenario can be examined by modifying the example shown in Figure 5 to change the operation of the eight wells from pumping to injecting and by adding a major pumping well in the center of the circle. The single pumping well will withdraw 1,000m³/day from the plume. The withdrawn water will be treated and re-injected into the eight injections wells at 125m³/day each. At zero to low flow velocities, the injected water flows radially toward the central pumping well, forming a closed loop for recovery and treatment of the plume (Figures 6A and 6B). At moderate to high natural flow velocities, the recovery loop is broken and an increasing amount of the injected water and the plume are swept away by the regional flow (Figures 6C and 6D). It must be emphasized that the cones of impression or depression of the wells overlap significantly for all of the multiwell examples discussed so far. Despite those overlaps, the net surface resulting from the natural gradient and the

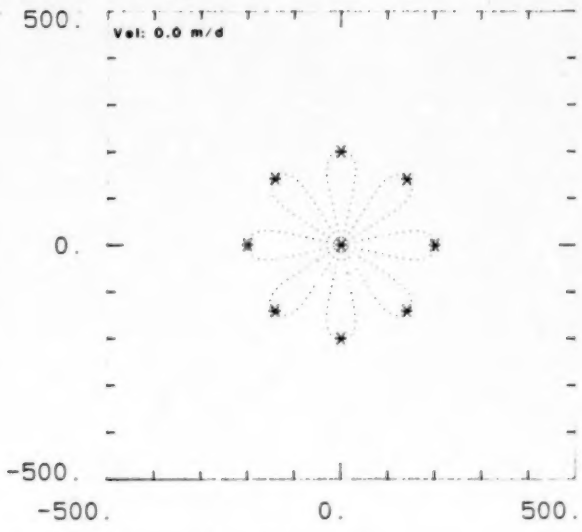

Figure 6A. Stagnant aquifer conditions

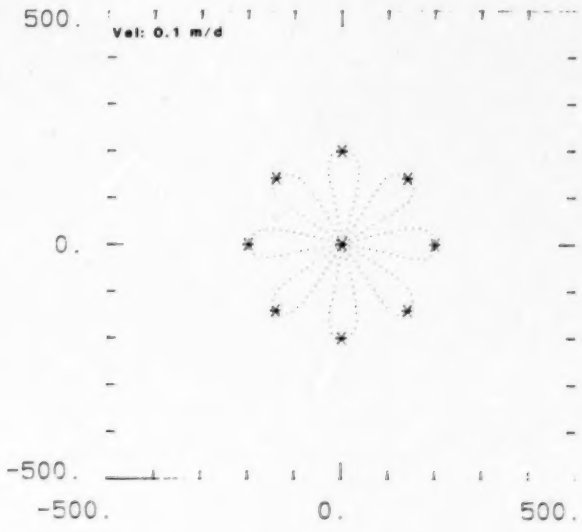

Figure 6B. Mild hydraulic gradient (0.0001)

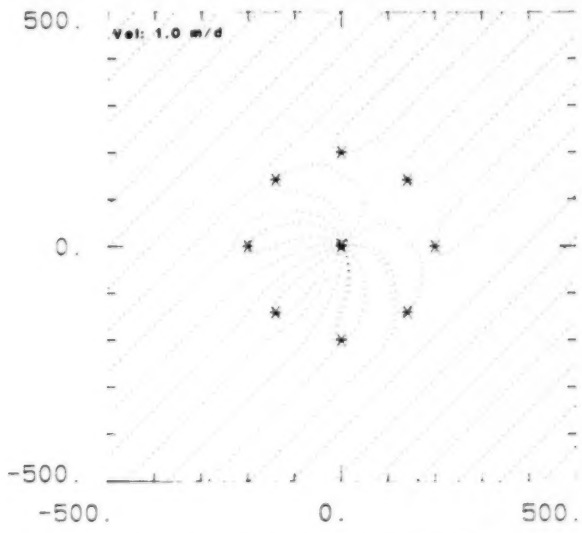

Figure 6C. Moderate hydraulic gradient (0.001)

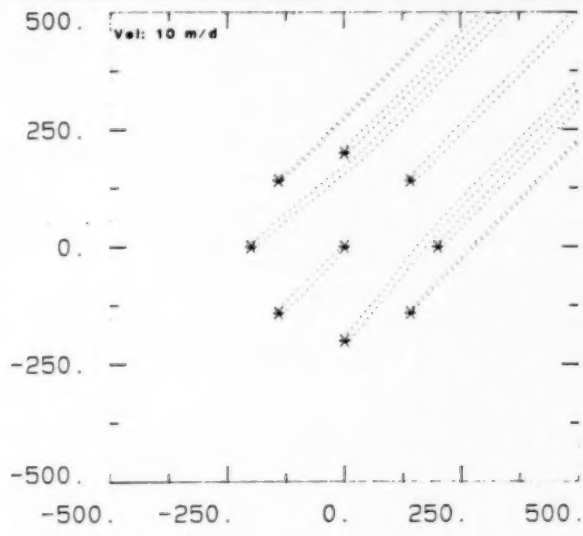

Figure 6D. Steep hydraulic gradient (0.01)

Figure 6. Flow line plots for a single well discharging 1,000m³/day, encircled by eight wells injecting 125m³/day into an aquifer with 10m saturated thickness, 100m/day hydraulic conductivity and 0.10 porosity

NOTE: Scale is in meters and natural flow proceeds from lower left-hand corner to upper right-hand corner of each plot at the velocity indicated.

water level changes due to pumpage and/or injection is shaped such that the streamlines are truly as presented here. For further discussion of capture zones and velocity distribution plots, see Keely and Tsang (1983). The detailed theoretical development and source code listings for the models that were used to generate the stream line plots shown here are given in Javandel et al. (1984).

A Little More Detail

It was quite clear in each of the preceding examples that the pumping strategy began to fail as the natural flow velocities became appreciable. The tendency to fail is generally becoming evident at a natural flow velocity of 1.0m/day and is beyond question at a natural flow velocity of 10m/day. Figure 7 shows that failure of each design is certain at 5.0m/day as well; the point at which the flow lines break through must be at much lower natural flow velocities.

In Figure 8 the natural flow velocity has been reduced to 0.5 and 0.4m/day for the last two examples only. Breakthrough of the streamlines (failure of the pumping strategy) occurs somewhere between the 0.4 and 0.5m/day natural flow velocities. Similar comparisons for the first two examples are not presented because flow line breakthrough does not apply to the first example (a single production well) and the flow line did not indicate breakthrough at 1.0m/day for the second example (a line of five wells).

The presence of an unknown well is being studied in Figure 9. A major pumping well (1,000m³/day) has been arbitrarily located downgradient of the same line

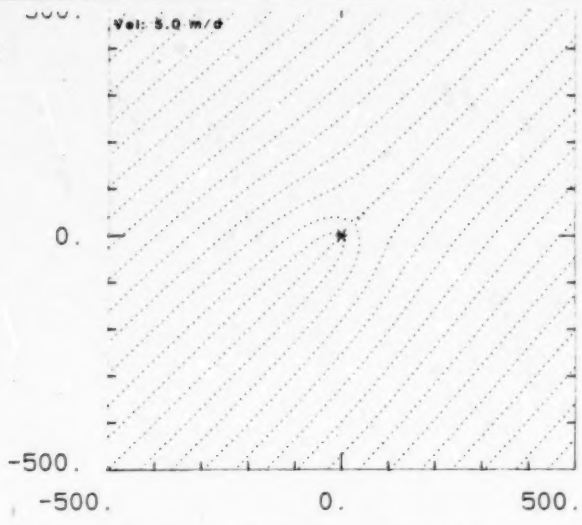

Figure 7A. Single well discharging 1,000m³/day

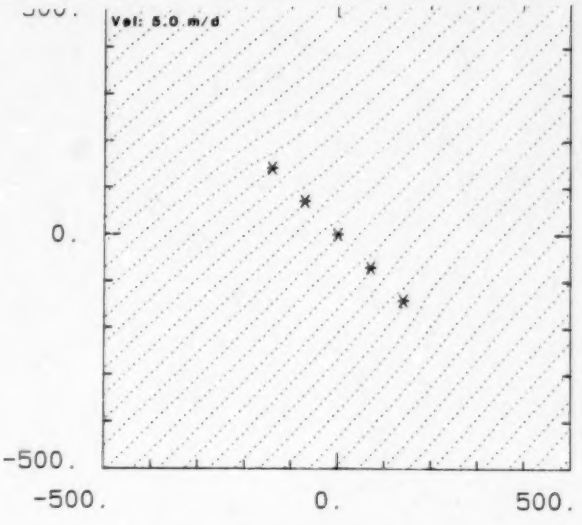

Figure 7B. Line of five wells, each discharging 200m³/day

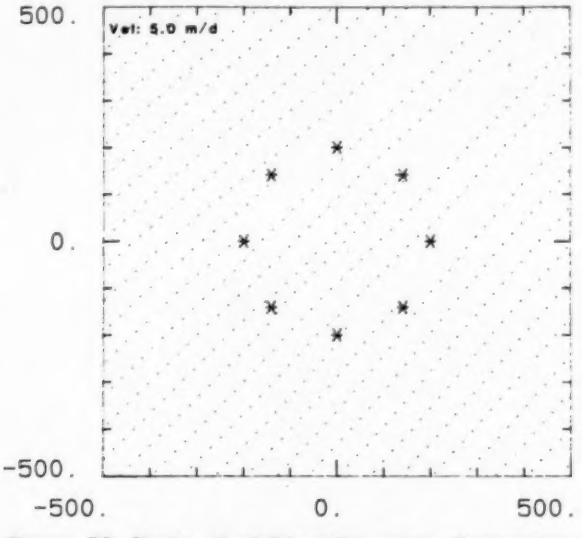

Figure 7C. Circle of eight wells, each discharging 125m³/day

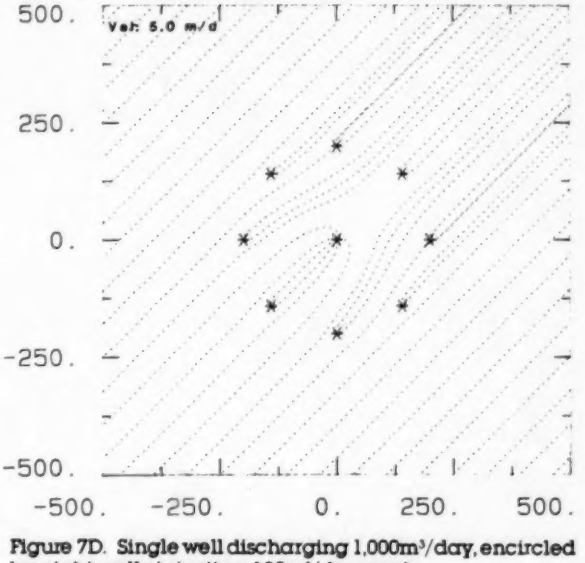

Figure 7D. Single well discharging 1,000m³/day, encircled by eight wells injecting 125m³/day each.

Figure 7. Comparison of pumping arrays in an aquifer with 10m saturated thickness, 100m/day hydraulic conductivity, 0.10 porosity and 0.005 hydraulic gradient

NOTE: Scale is in meters and natural flow proceeds from lower left-hand corner to upper right-hand corner of each plot at the velocity indicated.

of five wells discussed in the second example. Naturally, under stagnant aquifer conditions, the unknown well creates a hydraulic divide by distorting the flow field, but it does not cause breakthrough of the flow line from across the line of five wells (Figure 9A). With a natural flow velocity of 0.5m/day, however, flow lines do begin to break through the line of five pumping wells (Figure 9B). Substantial failure of the pumping scheme occurs at 1.0m/day natural flow velocity (Figure 9C). Contrast the onset of breakthrough due to unknown pumpage (Figure 9B) with the same situation in the absence of the unknown pumpage (Figure 9D). The impact of the unknown well is staggering, not only because flow line breakthroughs are occurring, but the collective size of the capture zones of the five pumping wells is being substantially reduced.

Another illustration of the impact of an unknown well on the effectiveness of a pumping scheme is shown in Figure 10, which is the same example as discussed earlier (Figure 6) for a closed-loop aquifer rehabilitation system. Under stagnant aquifer conditions, the unknown well diverts flow away from two of the injection wells (Figure 10A). At 1.0m/day natural flow velocity, the unknown well diverts flow from five of the eight injection wells (Figure 10B). It also allows flow to break away from the well field entirely, as indicated by the streamline leaving the uppermost injection well and heading downgradient in Figure 10B. The regional flow lines were omitted from Figure 10 and some of the diagrams in previous figures because inclusion of those flow lines would create confusion due to the excessive number of plotted points.

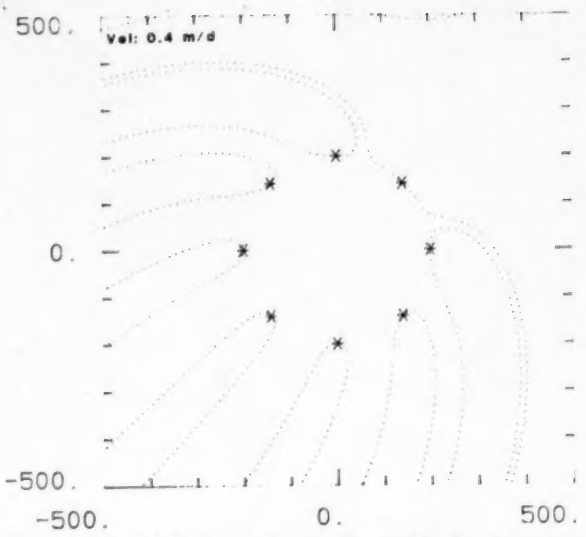

Figure 8A. Circle of eight wells, each discharging 125m³/day with 0.0004 hydraulic gradient

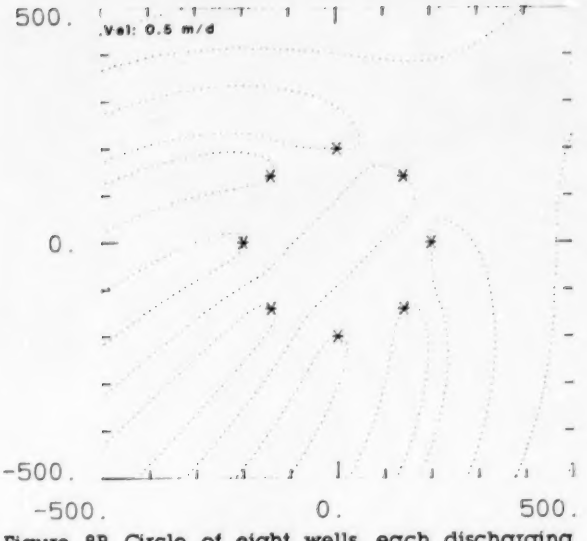

Figure 8B. Circle of eight wells, each discharging 125m³/day, with 0.0005 hydraulic gradient

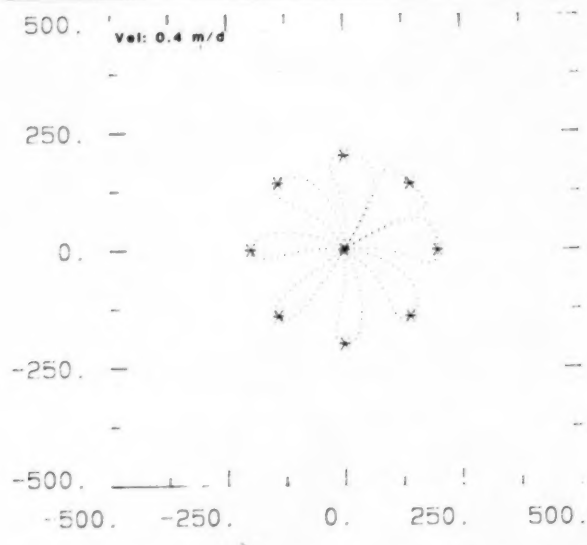

Figure 8C. Single well discharging 1,000m³/day, encircled by eight wells injecting 125m³/day each, with 0.0004 hydraulic gradient

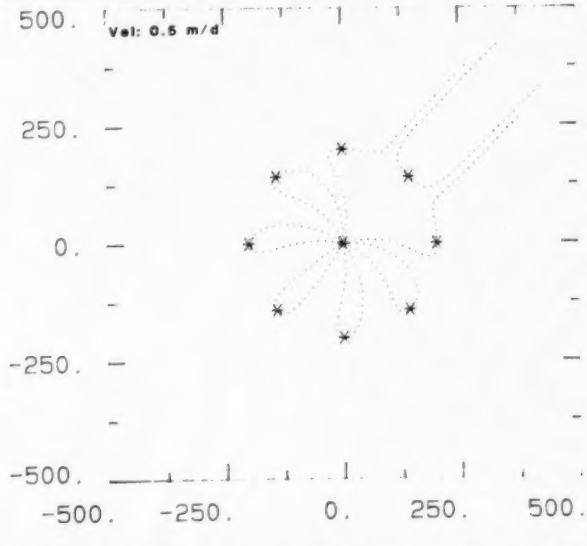

Figure 8D. Single well discharging 1,000m³/day, encircled by eight wells injecting 125m³/day each, with 0.0005 hydraulic gradient

Figure 8. Detailed views of the onset of flow line breakthroughs for two plume control strategies in an aquifer with 10m saturated thickness, 100m/day hydraulic conductivity and 0.10 porosity

NOTE: Scale is in meters and natural flow proceeds from lower left-hand corner to upper right-hand corner of each plot at the velocity indicated.

Conclusions

Heterogeneity, anisotropy, partial penetration and so on distort drawdown patterns and associated velocity distributions. If known, such influences can be used to enhance recovery efficiencies for remedial actions. If unknown, such influences may cause recovery efficiencies to be substantially lowered. Similarly, predictions of plume migration in non-ideal aquifers under non-pumping/natural flow conditions will be strengthened by specific knowledge regarding the occurrences, extent and magnitude of the non-ideal condition(s). Such predictions may be seriously in error if non-ideal conditions are not evaluated properly.

Denial of property access, loss by vandalism and unpredictable operation of nearby wells are also major sources of uncertainty in predicting contaminant migration and in designing remedial actions. Though commonly perceived to be less of an impact on optimizing pumping strategies than non-ideal aquifer conditions, these factors may indeed be the most uncontrollable and the most detrimental to operational success. Other factors that have major impacts are the physiochemical attenuation and biotransformation potentials of the individual contaminant; it is not yet economically feasible to conduct adequately detailed studies of these potentials on a routine site-specific basis. Finally, a factor often overlooked that greatly impacts optimization efforts is the risk of

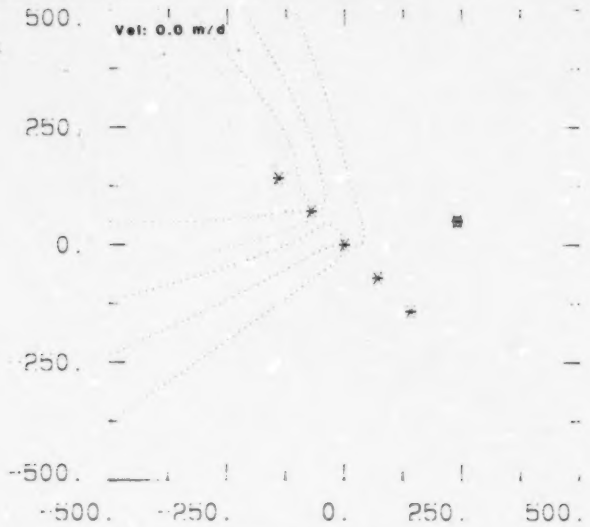

Figure 9A. Stagnant aquifer conditions

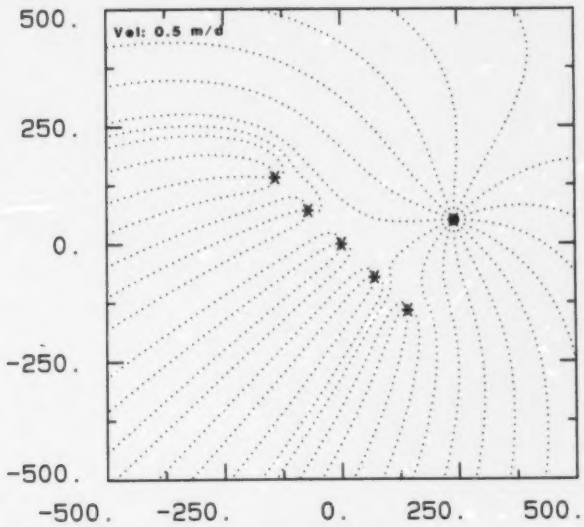

Figure 9B. Hydraulic gradient of 0.0005

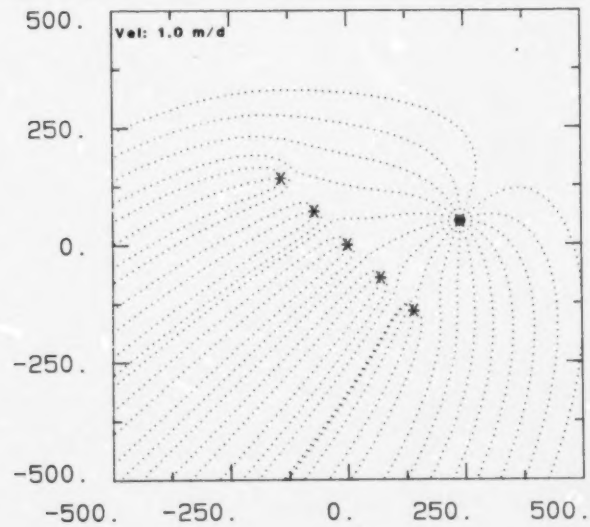

Figure 9C. Hydraulic gradient of 0.001

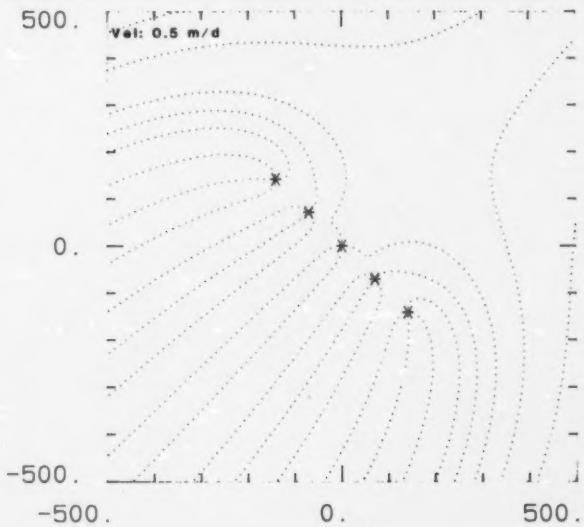

Figure 9D. Hydraulic gradient of 0.0005—without the unknown well

Figure 9. Influence of an unknown well discharging 1,000m³/day on flow line breakthroughs for a line of five wells discharging 200m³/day each from an aquifer with 10m saturated thickness, 100m/day hydraulic conductivity and 0.10 porosity

NOTE: Scale is in meters and natural flow proceeds from lower left-hand corner to upper right-hand corner of each plot at the velocity indicated.

mechanical and electrical operational failure; adequate contingency plans must provide certain minimal levels of excess/reserve capacity and redundancy of key system components.

The capture zones of wells do not equal their associated zones of pressure influence (cones of depression), except for stagnant aquifer conditions. Velocity distribution plots must be constructed to define potentials of contaminant migration. In particular, plotting the streamlines for various scenarios involving pumping and/or injection wells subject to a specific natural flow velocity can greatly assist the ground water professional in selection of an optimal pumping strategy.

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Disclaimer

Although this article was produced by an employee of the United States Environmental Protection Agency, it has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency; no official endorsement should be inferred.

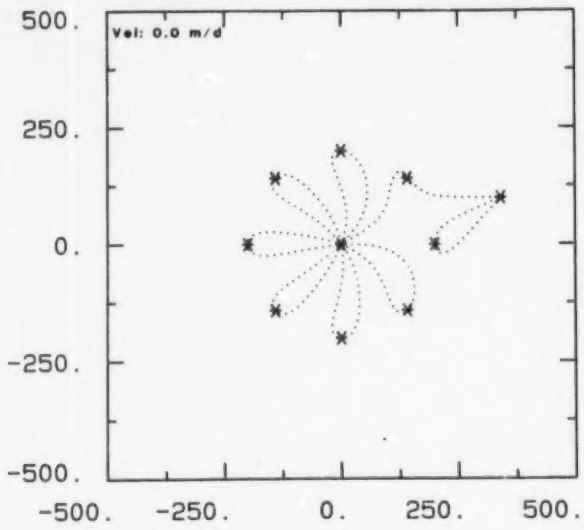

Figure 10A. Stagnant aquifer conditions

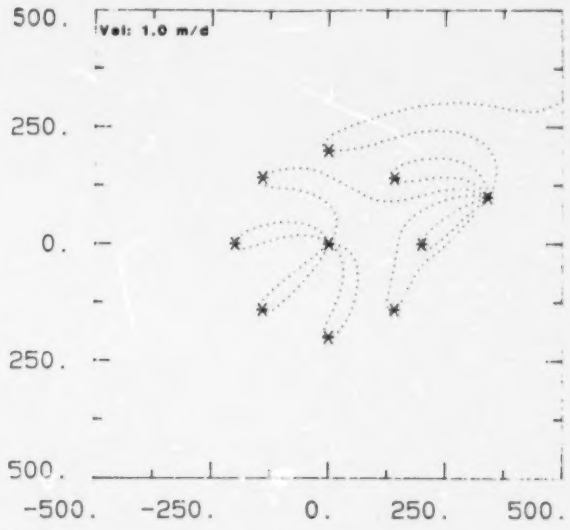

Figure 10B. Hydraulic gradient of 0.001

Figure 10. Influence of an unknown well discharging 1,000m³/day on flowline breakthroughs for a single well discharging 1,000m³/day that is encircled by eight wells injecting 125m³/day into an aquifer with 10m saturated thickness, 100m/day hydraulic conductivity and 0.10 porosity.

NOTE: Scale is in meters and natural flow proceeds from lower left-hand corner to upper right-hand corner of each plot at the velocity indicated.

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Biographical Sketch

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